POSTER

DISCOVERY OF COLD, LUMINOUS ISO-FIRBACK SOURCES WITH KECK SPECTROSCOPY

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We present Keck spectroscopy and UKIRT near-IR imaging observations of two 170\,\m-selected sources from the {\it ISO}-FIRBACK survey which have faint counterparts in the optical, and $r-K\sim5$. Both sources were expected to lie at $z>1$ based on their far-infrared, submillimeter and radio fluxes, assuming a similar spectral energy distribution to the local ultra-luminous infrared galaxy (ULIRG) Arp\,220. However, our spectroscopy indicates that the redshifts of these galaxies are $z<1$: $z=0.91$ for FN1-64 and $z=0.45$ for FN1-40. While the bolometric luminosities of both galaxies are similar to Arp\,220, it appears that the dust emission in these systems has a characteristic temperature of $\sim$30\,K, much cooler than the $\sim$50\,K seen in Arp\,220. Neither optical spectrum shows evidence of AGN activity. If these galaxies are characteristic of the optically faint FIRBACK population, then evolutionary models of the far-infrared background must include a substantial population of cold, luminous galaxies. These galaxies provide an important intermediate comparison between the local luminous IR galaxies, and the high redshift submillimeter-selected galaxies, for which there is very little information available.

Background:

The spectral shape of the far-infrared background (FIRB) detected by {\it FIRAS} at 100\,\m--4\,mm and {\it DIRBE} at 140 and 240\,\m\ (Puget et al.\ 1996; Fixsen et al.\ 1998) indicates a peak at ~200\,\m\ with energy comparable to the optical/UV background. This peak arises from optical/UV radiation from star formation and AGN activity in obscured galaxies at $z\gg 0$ which is absorbed by dust and reradiated in the far-infrared. This obscured population of galaxies could host approximately half of the massive star formation activity over the history of the Universe (e.g.~Blain et al.\ 1999).

Far-infrared surveys at wavelengths close to the peak of the FIRB provide a powerful route for understanding the properties of the obscured activity in the distant Universe and its relevance to the formation and evolution of both galaxies and super-massive black holes. The FIRBACK (Far-InfraRed BACKground, Dole\ 2000) survey obtained wide-field imaging at 170\,\m\ with the PHOT instrument on-board {\it ISO} satellite in three separate regions of the sky chosen for low Galactic cirrus foreground. FIRBACK is the most reliable and deepest (σ(170\m)~ 40\,mJy) infrared census at wavelengths near the peak in the FIRB. The FIRBACK sources down to 120\,mJy account for about 10\% of the FIRB seen by COBE at 140--240\,\m\ (Puget et al.\ 1999). Evolutionary models (Dole et al.~2001,

Lagache et al.~2002) suggest that the sources identified by FIRBACK comprise both star-forming galaxies at low redshifts, $z\sim 0.1$, and a population of much more luminous galaxies at higher redshifts.

The models predict that a quarter of the FIRBACK sources should have $z>0.5$, with a tail reaching beyond $z=1.5$. The sources in this high-redshift tail provides the strongest constraints on the evolution of the population contributing to the peak of the FIRB at ~ 200\m. For this reason the identification and study of these galaxies is of particular interest (Sajina et al.~2002, Dennefeld et al.~2002).

Observations:

We observed FN1-40 and FN1-64 in the K-band at UKIRT using the Fast Track Imager (UFTI) as part of the on-going identification campaign of FIRBACK sources. The K-band imaging of both sources is shown in Fig.~1. In both sources the component which is coincident with the radio emission, and by implication is the source of the luminous far-IR emission, is very red, $(R-K)\sim5$.

Spectroscopic observations of FIRBACK FN1-40 and FN1-64 were taken using the Echellette Spectrograph and Imager (ESI) on the Keck\,II telescope in 2001 July.

The spectra of both FN1-40/J1 and FN1-64/J2 show a series strong emission lines in the red, we identify the strongest of these as [O{\sc ii}]3727, [O{\sc iii}]5007 and for FN1-40: Hα. Based on these identifications we determine a redshift of $z=0.45$ for FN1-40/J1 and $z=0.91$ for FN1-64/J2.

Results:

Figure~3 depicts the measured near-IR through radio photometry for the two FIRBACK galaxies. A template fit from SED library of Dale et al.\ (2001,2002) is overlayed, encompassing the mid-IR through radio wavelengths.

From our fits we estimate that galaxies are relatively cool with T$_{\rm d}$=25.7$\pm$0.4\,K and β=1.76$\pm$0.01 for FN1-40; and T$_{\rm d}$=30.8$\pm$0.7\,K with β=1.68$\pm$0.02 for FN1-64.

In terms of bolometric far-IR luminosity (40 to 200\m), using the best fitting SEDs we estimate that FN1-40 has a luminosity of around L$_{\rm FIR}\sim 7\times10^{11}$\,L$_\odot$, placing it just in the ULIRG category. FN1-64 is more luminous, with L$_{\rm FIR}\sim 4\times10^{12}$\,L$_\odot$, placing it well into the ULIRG class and showing that it is four times as luminous as Arp\,220.

A comparison of the morphologies of these two FIRBACK sources, multiple components separated on scales of ~ 10\,kpc, with local ULIRGs (Goldader et al.\ 2001) suggests a similarity with ``early stage mergers" such as VV\,114. Equally, the tendency for the radio emission (and therefore presumably the far-IR) to come from the redder component is also shared with local ULIRG samples. However, there are differences: The far-IR curves for FN1-40/FN1-64 are fit by cool SEDs, which would normally be accompanied by a modest L$_{\rm FIR}$/L$_{\rm optical}$ ratio for such early stage mergers (Dale et al.\ 2000).

Conclusions:

We can conclude that the dust temperature distribution at higher redshifts is consistent with that observed locally (or alternatively, that the characteristic temperature of a ULIRG doesn't increase dramatically out to $z\sim1$). Note that this is not necessarily the expected result. For instance, different temperatures distributions for similar luminosity ULIRG populations at $z=0$ and $z=1$ could arise due to different geometry of the active region, or different chemical properties of the dust. Complete redshift distributions for the FIRBACK population will be required to carefully test the dust temperature distributions at low and high redshift.

Future needs of instrument technologies:

1) Spatial resolution in the IR is crucial to understand the physics of cold, luminous galaxies. Currently we don't know if FIR/radio relation holds at high redshifts to attempt to derive FIR from radio interferometry.

2) Sensitivity issues for a large population of cold galaxies at high redshift. We will need to probe significantly deeper than SIRTF over a wide field to fully understand the connection between IR and sub-mm galaxies.